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Prospects of TEVATRON Upgrade*

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Abstract

Following a brief review of the 1987 Fermilab collider run and the present status of the 1988 run, upgrade plans for the near-term (1988-1992) are described. For further luminosity upgrades beyond 1992, several scenarios are currently being discussed, one of which includes the construction of two new 20 GeV rings which could raise the proton-antiproton collider luminosity by a factor of 50 over the original Tevatron I design. Another possible project, the construction of a high luminosity proton-proton collider, has also been investigated in detail. A third scenario, involving a new Main Injector to replace the Main Ring and a new higher energy superconducting synchrotron, is presently being examined. It is hoped that this will result in a proposal to be submitted to DOE for FY91. The major issues concerning these options are presented.

1 THE FIRST COLLIDER RUN

May 11, 1987 marked the end of the first Tevatron colliding beams physics run. The three month run saw the collider deliver a total integrated luminosity of 70 nb^{-1} over a total of 92 stores. The initial luminosity observed on each store grew by an order of magnitude each month, reaching a typical value of $1 \times 10^{29} cm^{-2} sec^{-1}$ by the end of the run. The typical luminosity lifetime of each store was 10 hours. This lifetime increased from about 7–8 hours at the beginning of a store to about 15–20 hours by the end. The lifetime is about half of the Tevatron I design value. Though the initial luminosity of $1 \times 10^{29} cm^{-2} sec^{-1}$ was the goal for this initial run, it is still an order of magnitude below that in the original design report.

*Operated by Universities Research Assn., Inc., under contract with the U. S. Department of Energy.

For an accelerator in which two round Gaussian beams are colliding head-on, the luminosity is given by

$$\mathcal{L} = \frac{B f_o N_p N_{\bar{p}}}{4\pi\sigma^2} = \frac{3 B f_o N_p N_{\bar{p}}}{2\beta^* \epsilon_N}\gamma$$

where f_o is the revolution frequency, N_p and $N_{\bar{p}}$ are the numbers of protons and antiprotons in each bunch, B is the number of bunches of each type of particle, and σ is the standard deviation of the transverse beam distribution. The second expression has the luminosity rewritten in terms of the amplitude function at the interaction point β^*, the normalized transverse beam emittance ϵ_N (95%), and the beam energy $\gamma = E/m_o c^2$.

As reported elsewhere, [1] gains needed to be made in the antiproton stacking rate and transfer efficiencies, as well as a reduction in the beam emittance growth rate. Only 34% of the antiprotons extracted from the Accumulator ring made it to low-beta. The stacking rate was also down by about a factor of 8 from the initial design. The luminosity lifetime was substantially poorer than expected from beam-gas and intrabeam scattering effects, dominated by growth of proton and antiproton transverse emittances.

While some of the parameters are fixed, at least for the moment, gains can be made in the collider luminosity by better controlling the number of particles that reach the desired value of β^* and by better controlling the transverse emittances. This means not only improving the efficiency of the collider itself, but also the efficiencies of the other accelerators along the chain.

2 IMPROVEMENTS FOR THE 1988 RUN

Several major improvements were made during the three month long maintenance period prior to the 1988 collider run. The most significant modification, in fact one principal reason for the shutdown period, was the revision of the Main Ring vertical overpass through the D0 region. The original design of this overpass had left a wave of vertical dispersion throughout the Main Ring lattice. The relatively small increase in beam size due to this dispersion was thought not to be of much concern and hence the mismatch was left uncorrected. The major problem arose during transfers of coalesced bunches from the Main Ring into the Tevatron. The mismatched vertical dispersion functions were equivalent to an injection steering error for an off-momentum particle. As a result, the vertical transverse emittance of the coalesced beam grew by about a factor of two during the transfer. The new D0 design, which included four new vertical bending magnets around D0, corrected

[1] Dugan, G., "The Tevatron: Status and Outlook," European Particle Accelerator Conference, Rome, 1988.

this mismatch in addition to reducing the amplitude of the overall dispersion wave around the rest of the accelerator.

New controls hardware and software now permit fine control of the betatron tunes and chromaticity of the Tevatron during injection and at the beginning and end of the acceleration process. For stability, the Tevatron chromaticity needs to be held to a value below ~ 2. During the initial collider tests in 1985, it was discovered that the chromaticity would gradually increase with time while the accelerator was idle at its injection energy of 150 GeV. As soon as the machine began to accelerate particles, the chromaticity would change abruptly, in a then unknown fashion, sometimes leading to large beam loss.

Recently, magnetic field measurements at the Fermilab Magnet Test Facility have revealed the time behavior of the sextupole component of the main dipole magnets both while at the injection energy and during acceleration. It was discovered, quite unexpectedly, that the sextupole component changed rapidly and significantly, generating a change in the machine chromaticity by about 30 units during the first second after acceleration began. This behavior is now basically understood and the new controls hardware permit its correction.

In addition, a source of emittance growth during beam storage was discovered and corrected. This source turned out to be the capacitor-bank charging power supplies for the proton and antiproton abort kickers. Studies performed during a store in February, 1988, revealed that the proton horizontal emittance growth rate could be reduced from 3.5 π *mm-mrad/hr* to 0.75 π *mm-mrad/hr* when the horizontal abort kicker system was de-energized. The filtering of these power supplies has been improved in an effort to reduce this effect.

These improvements, along with improvements made to the effective aperture of the antiproton accumulator ring and the introduction of six bunches of antiprotons colliding with six bunches of protons ("6-on-6" as opposed to the "3-on-3" operation last year), raised the expected initial luminosity to $3 \times 10^{29} cm^{-2} sec^{-1}$ for the current run. The goal for this eleven month run is to produce a total integrated luminosity of 1000 nb^{-1}.

Within the first three weeks of operation, the collider was back to the running conditions of the previous year. During the first ten stores, initial luminosities on the order of $1 \times 10^{29} cm^{-2} sec^{-1}$ were reached, the transfer efficiency for antiprotons from the accumulator to low-beta was 50% (up from last year's best effort of 30%), and antiprotons were being accumulated at the rate of 10^{10} per hour. Since then, the initial luminosity has been routinely $5 \times 10^{29} cm^{-2} sec^{-1}$ and the antiproton transfer efficiency has been as large as 85%. A single store has lasted for 40 hours and another has produced 42 nb^{-1} of integrated luminosity. After only 10 weeks of operation, the total luminosity delivered by the collider has been 360 nb^{-1}, as depicted in Fig. 1.

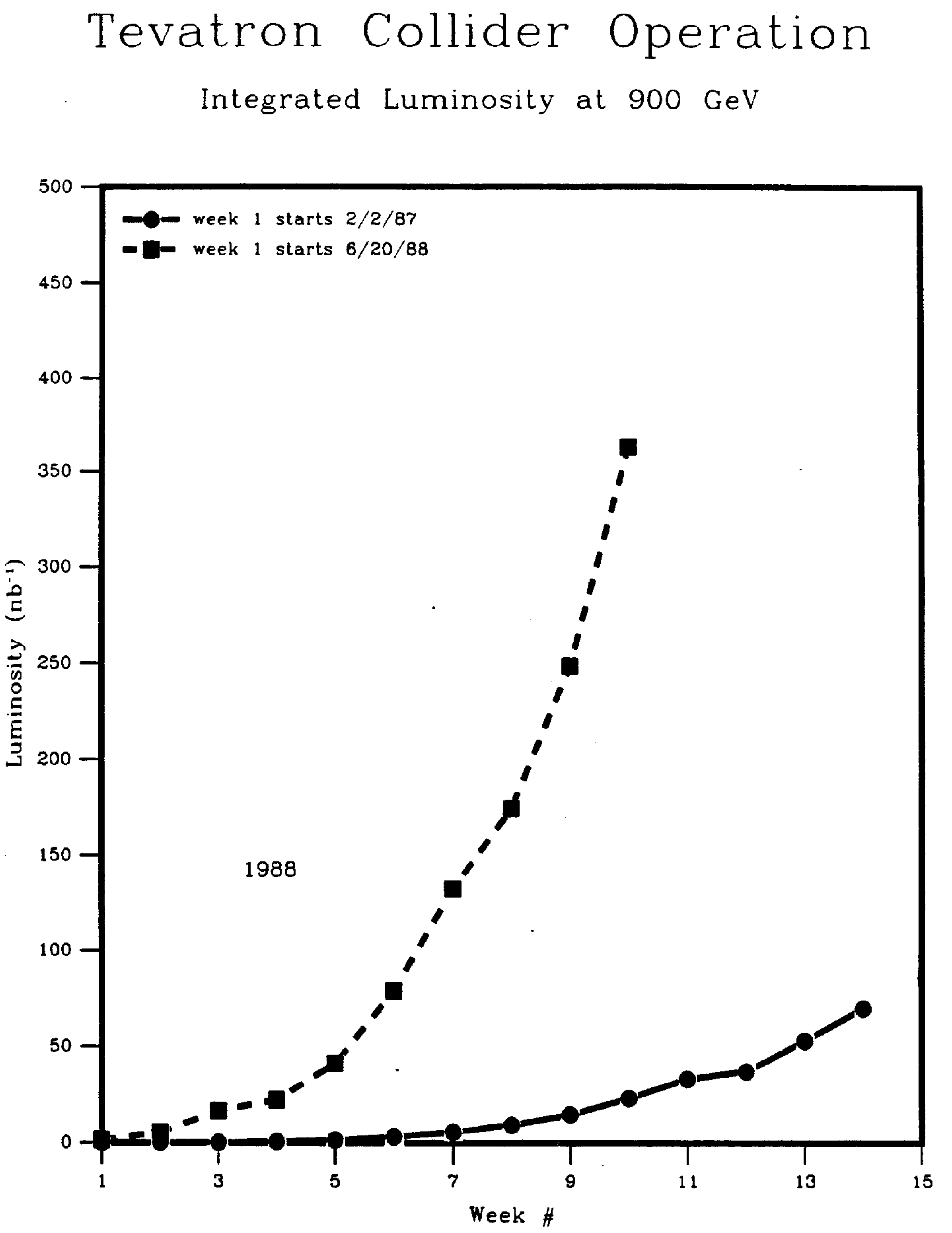

Fig. 1 — Integrated luminosity delivered by the Tevatron Collider during the three month run of 1987, and so far during the 1988 run.

3 NEAR-TERM COLLIDER UPGRADES

A principal problem facing a colliding beams accelerator operating with many bunches is the shift in the betatron oscillation frequency experienced by a particle as it passes through oncoming bunches. Due to this effect, particles of small oscillation amplitudes undergo a small change in the number of oscillations per turn by an amount given by

$$\Delta\nu = H \cdot \frac{3N_p r_o}{2\epsilon_N}$$

where H is the number of passages through oncoming bunches per turn, r_o is the classical radius of the particle, and ϵ_N is the normalized emittance (95%). The expression above contains the proton bunch intensity, and hence reflects the tune shift experienced by the antiprotons. Though the protons undergo a similar tune shift, the effect is typically stronger for the antiproton motion due to the larger intensities found in the proton bunches.

The beam-beam tune shift, $\Delta\nu$, gives a rather hard limit to the allowable phase space density. Though the ideal operating tunes in the two transverse degrees of freedom may be comfortably far from lower-order resonances, particles affected by the beam-beam interaction may find themselves near resonances. Fig. 2 is a plot of vertical tune vs. horizontal tune in the vicinity of the Tevatron operating point. Sum and difference resonance lines through seventh order are indicated. The width of the region around the operating point defines an upper bound for the allowable beam-beam tune shift. The Tevatron collider, during "6-on-6" operation, has

$$\Delta\nu = 12 \cdot \frac{3(6 \times 10^{10})(1.5 \times 10^{-18} m)}{2(20\pi \times 10^{-6} m)} = .025,$$

very much near this upper bound. Further increase in the number of protons per bunch or further reduction of the beam emittance will lead to loss of antiprotons and a subsequent shortening of the luminosity lifetime. (In fact, in recent weeks, the technique of intentionally enlarging the proton emittance in exchange for higher proton bunch intensity has become necessary during collider operation.)

Let us rewrite the expression for the initial luminosity of a collider in terms of the beam-beam tune shift:

$$\mathcal{L}_o = \frac{\gamma f_o}{r_o \beta^*} \cdot \frac{B N_{\bar{p}}}{H} \cdot \Delta\nu.$$

So long as the counter-rotating beams of particles and antiparticles continue to circulate on the same orbits, further improvements to the initial luminosity entail reduction of the amplitude function at the interaction point, increasing the total number of circulating antiprotons, and increasing the beam energy. The last item, of course, would have other physics pay-offs as well.

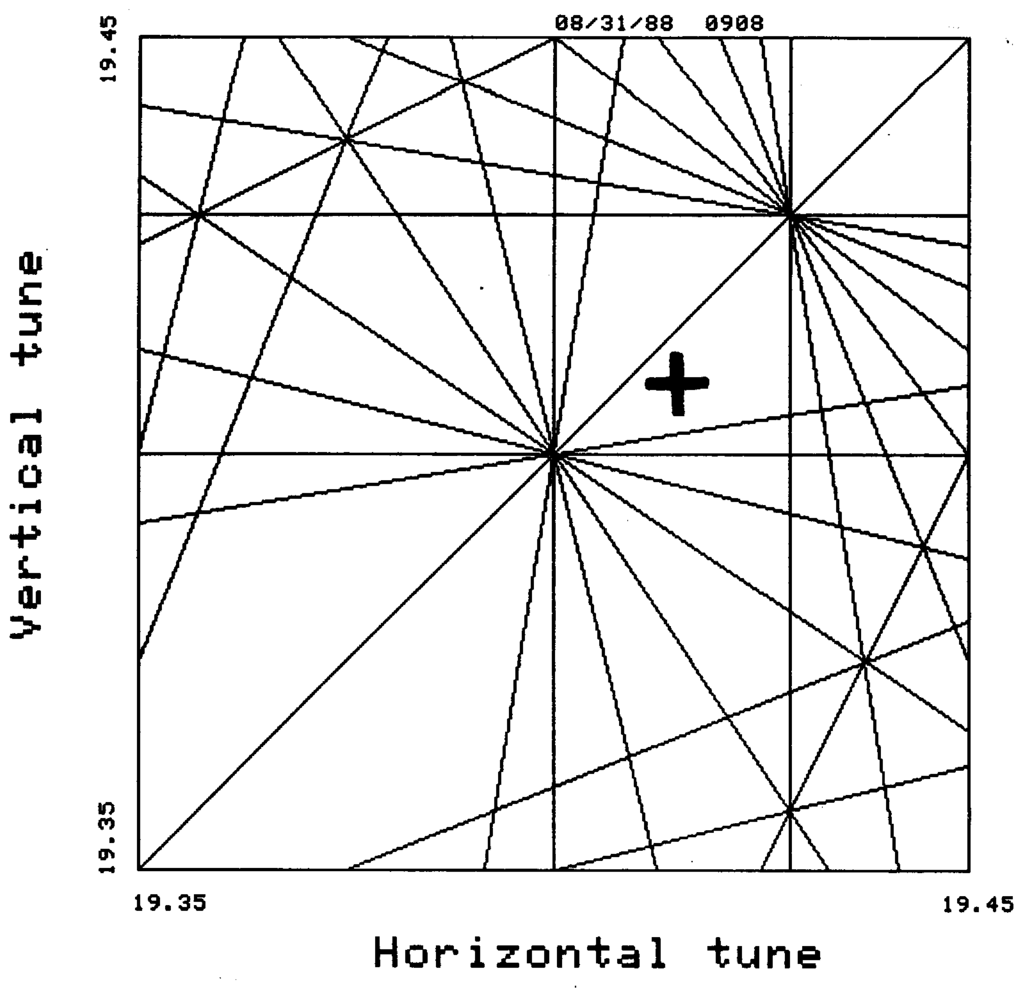

Fig. 2 — Vertical tune vs. Horizontal tune in the vicinity of the Tevatron operating point, indicated by the "plus-sign." The lines represent resonance conditions through seventh order.

Presently, programs are underway at Fermilab to push these parameters toward higher luminosities. A new interaction region design will permit β^* to reach values as low as 25 cm. Additional refrigeration will allow the superconducting magnets to operate at slightly lower temperatures ($4°K$) and hence allow the magnets to run at ten percent higher currents, making the accelerator a true *Tev*atron. Already, more than 4×10^{11} antiprotons have been accumulated in the antiproton source at one time. Providing stacks in excess of 5×10^{11} antiprotons can become routinely available , it is conceivable that total antiproton intensities of 2.5×10^{11} could be delivered to low-beta in the not-too-distant future. Assuming the proton intensity and transverse emittances are pushed to the beam-beam limit, the above parameters lead to an initial luminosity of

$$\mathcal{L}_o \approx 5 \times 10^{30} cm^{-2} sec^{-1}.$$

It is hoped that this luminosity can be realized during the next three to four years.

One drawback to this scenario may be the increased number of interactions per hit seen by the detector. Assuming a typical cross section of 100 mb for strong interactions, with the above luminosity the detector should expect to see an average of 1.5 interactions per hit, assuming "6-on-6" operation. A way around this problem would be to distribute the particles among a larger number of bunches. This could require separated orbits outside the interaction regions to avoid a build-up of the beam-beam tune shift.

During the same four year period, upgrades will also be made in an effort to improve the antiproton stacking rate. A particularly significant aspect is the doubling of the energy of the Fermilab Linac. This project is under consideration by DOE for funding in FY90. [2] Four of the downstream accelerating cavities are to be replaced with more efficient, higher frequency, higher accelerating gradient structures to increase the output kinetic energy of the Linac from 200 MeV to 400 MeV. Space charge forces at 200 MeV cause the transverse emittances to grow significantly upon injection into the Booster synchrotron. With the higher energy beam, this effect should be dramatically reduced, permitting smaller emittance, more intense beams to be transmitted through the Booster and on to the Main Ring and Tevatron accelerators.

With these more intense beams, the antiproton production rate could conceivably be increased by 50 to 100 percent. This upgrade obviously will be a benefit to the fixed target program as well. Of course small emittance beams delivered to low-beta would also aid in the quest for higher luminosities, provided the machine is not beam-beam tune shift limited. Again, separated orbits may be the answer, and work is being done to explore this possibility.

In the meantime, upgrades to the antiproton source continue. Improvements to the target size, targetting rate, and the momentum aperture of the Debuncher ring,

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[2] "Antiproton–Proton Collider Upgrade: Linac," Conceptual Design Report, Fermilab, 1988.

together with the Linac upgrade, are expected to increase the antiproton production rate to $\sim 6 \times 10^{10}$ per hour.

4 1993 TO THE SSC ERA

To further increase the physics potential of the Tevatron collider, new large-scale projects are under consideration. While the above mentioned upgrades include the reduction of β^* and the reduction of the emittance, large gains in luminosity require large increases in the number of particles circulating the accelerator. For the proton-antiproton collider, the main concern is antiproton economics. To begin with, the Fermilab Accumulator ring design estimated its storage capacity as 5×10^{11} antiprotons. Though small upgrades of this number can possibly be achieved – recent measurements indicate twice this amount may be possible – orders of magnitude are not foreseen. Also, if higher luminosities could be acquired, higher stacking rates would be necessary to be able to replenish the antiprotons at an acceptable pace. A scenario for increasing the collider luminosity by a factor of 50 over the original Tevatron design goal has been investigated. [3] This project would include two new 20 GeV accelerators, one a proton booster ring, the other an antiproton storage ring.

Another approach to high luminosity is a proton-proton collider, thus bypassing all of the problems associated with producing and storing large numbers of antiprotons. This scenario has also been investigated in detail, [4] and involves the construction of a new tunnel to house the 150 GeV injector synchrotron, making room for a second superconducting ring in the main 4-mile tunnel. This option would be able to produce initial luminosities in excess of 200 times the original Tevatron I design goal.

New upgrade schemes are presently being investigated. These include a higher energy superconducting accelerator for proton-antiproton physics, and combinations of the above two scenarios. All of these options are described in more detail below.

4.1 20 GeV Rings and the $\bar{p}p$ Option

A study by the Fermilab Accelerator Division in 1987 investigated the need for and feasibility of constructing new accelerators as part of an effort to raise the Tevatron collider luminosity to $5 \times 10^{31} cm^{-2} sec^{-1}$. The primary goals of the two machines eventually designed were to provide more intense, smaller emittance proton beams to both the Tevatron collider as well as the antiproton source, and to provide storage and cooling for up to 4×10^{12} antiprotons.

[3] "Antiproton–Proton Collider Upgrade: 20 GeV Rings," Conceptual Design Report, Fermilab, 1988.

[4] "Proton–Proton Collider Upgrade," Conceptual Design Report, Fermilab, 1988.

The new antiproton storage ring, called the Antiproton Super Booster (ASB) would accept antiprotons from the Accumulator ring every hour or so. Since it would receive beam only rarely (compared to the Accumulator which receives beam every 2 seconds), the ASB would not require a stack-tail stochastic cooling system and thus should have an improved storage capacity. The accumulated antiprotons are then to be accelerated to 20 GeV and injected into the Main Ring. The reason for the choice of 20 GeV is expanded upon below.

Another feature of the ASB would be the capability to accept antiprotons from a previous Tevatron store for further stochastic cooling. These antiprotons would need to be decelerated in the Tevatron to 150 GeV, transfered to the Main Ring, decelerated to 20 GeV, then transfered to the ASB. This scheme would reduce the production requirements of the antiproton source as well as the length of storage time required in the collider before a new store can be initiated.

The second new accelerator would be the Proton Super Booster (PSB). A major source of beam loss in the Fermilab chain of accelerators is the Main Ring at its injection energy of 8.9 GeV. At this energy, the beam lifetime is roughly 3–5 seconds. Fig. 3 shows the Main Ring beam intensity and main bend magnet current vs. time as recorded in the Main Control Room. By the time the beam has reached an energy of approximately 20 GeV, no discernable lifetime is evident. This energy is also above the Main Ring transition energy (17.5 GeV), the crossing of which often leads to instability and beam loss.

A series of beam studies have been performed to investigate the behavior of beams at 20 GeV. These studies have shown that the reduced beam size at this energy, along with the improved magnet field quality and the reduced sensitivity to the residual gas in the vacuum chamber, yield a 20 GeV lifetime of many hundreds of seconds. This behavior is independent of beam intensity. Fig. 4 shows the result of one such measurement. The beam intensity is essentially constant over a period of ten seconds.

These two accelerators would be similar in size to the Booster and antiproton source. The rings would be concentric (for purely economic reasons) and would be situated on the outside of the Main Ring tunnel as depicted in Fig. 5. Each machine is in a separate enclosure, and a series of new beam transfer lines would allow access to any of the Booster-size rings during operation of any other.

4.2 The pp Option

A second upgrade option studied at Fermilab during early 1988 is that of a proton-proton collider. Here, the Main Ring is removed from the four mile enclosure and located elsewhere. In its place, a second superconducting accelerator which operates at 1 TeV is installed. Protons circulating in opposite directions in the two superconducting rings are brought into collision at B0 and D0. Since the two beams circulate in separate machines, the beam-beam tune shift is not a problem. Nearly

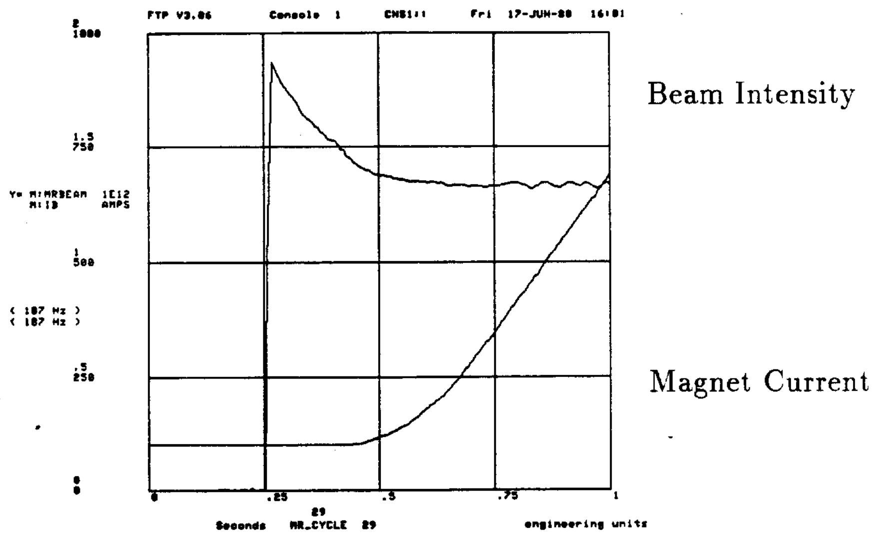

Fig. 3 — Main Ring beam current and Main Ring bend magnet current vs. time. The beam loss disappears after an energy of about 20 GeV is reached.

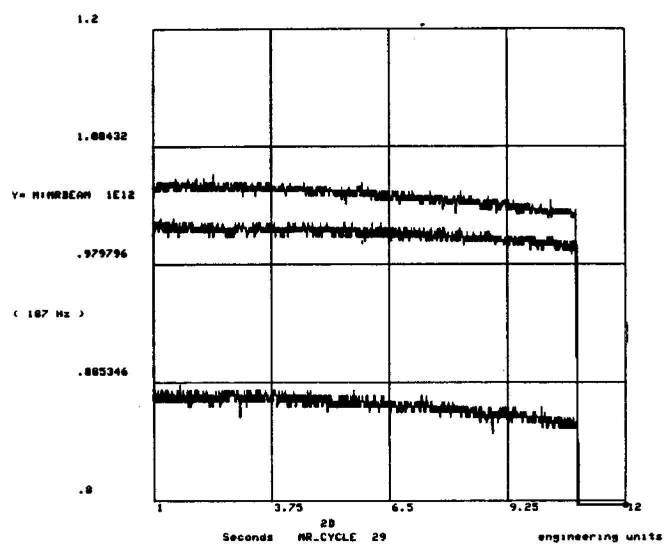

Fig. 4 — Main Ring beam current vs. time at a store condition of 20 GeV. Three beam pulses indicating a lifetime of many hundreds of seconds.

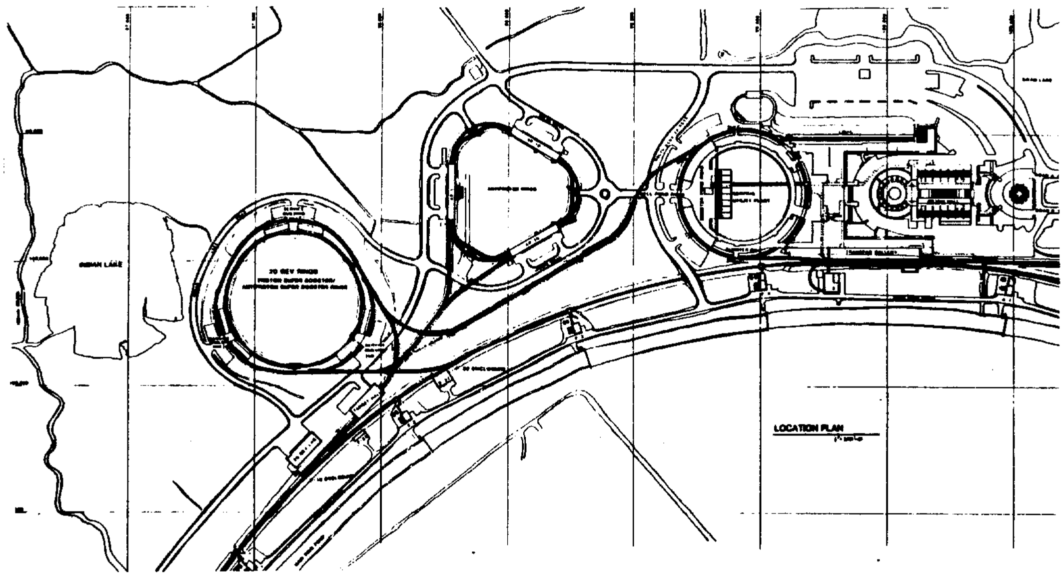

Fig. 5 — Site layout of 20 GeV Rings project.

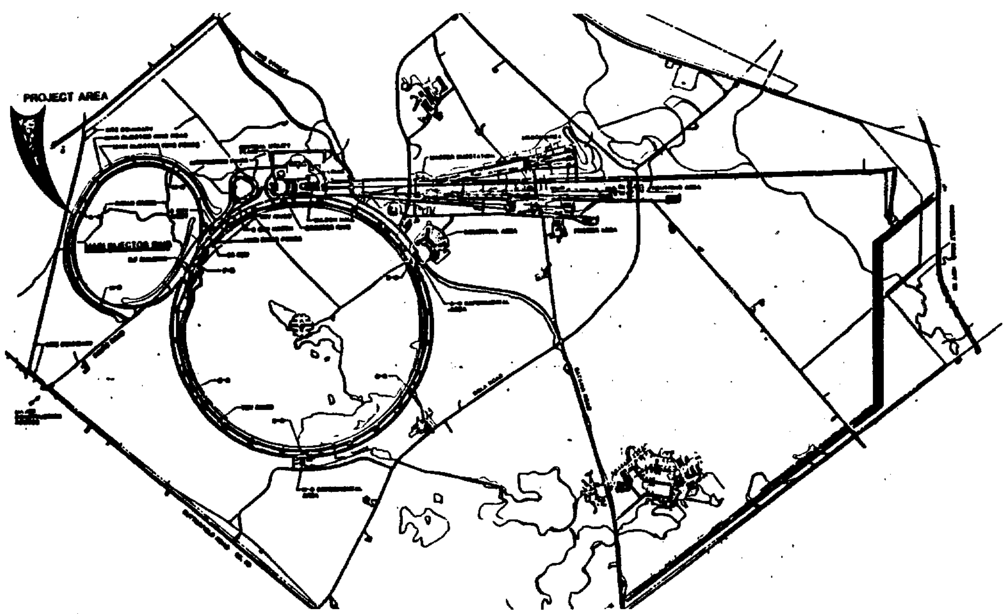

Fig. 6 — Site layout of new Main Injector for the proton-proton collider project.

all of the 1113 buckets of the present 53 MHz RF system could be occupied with particles. One immediately obtains an estimate of the luminosity of

$$\mathcal{L}_o = \frac{3Bf_oN_p^2\gamma}{2\beta^*\epsilon_N} \approx \frac{3\cdot 10^3\cdot(47750)\cdot(2\times 10^{10})^2\cdot 10^3}{2\cdot(25cm)\cdot(20\pi\times 10^{-4}cm)} = 2\times 10^{32}.$$

The finite crossing angle of the two beams at the interaction point will reduce this estimate by about 30 percent. However, the above computation does not even include the full benefits from the Linac upgrade. The very large potential luminosity as well as the exclusion of the very exacting antiproton production technology makes the proton-proton approach the more conservative route.

The new Main Injector would be one-half the circumference of the superconducting rings and will lie outside of the main enclosure, as shown in Fig. 6. Since the present 150 GeV Main Ring has routinely operated at 400 GeV in the past, the Main Injector can be comprised almost entirely of Main Ring components. Only the "B2" style dipole magnets would be used. These magnets have a larger vertical aperture than the "B1" style dipoles also used in the Main Ring. Recent magnetic measurements have shown that the B2 magnets are also of better field quality. To provide even stronger focussing, however, most of the Main Ring quadrupoles would be reinstalled. This stronger focussing, along with improved optics through the straight section, will ensure a small beam throughout the acceleration cycle. Since the magnets will be operating at approximately twice the current, the magnetic field quality at injection also will be significantly improved.

Transfers between the Main Injector and the superconducting accelerators occur at the F0 straight section. This is also the location of the accelerating cavities. The removal of the Main Ring-to-Tevatron transfer equipment at the E0 straight section leaves this region available for a possible third interaction region at some future date. Such an IR was not included in this design study.

The Main Injector must accelerate protons in both the clockwise and counterclockwise sense for injection into the two superconducting rings. The second Tevatron is located 50 *cm* above the present Tevatron and will have an identical focussing structure. A cross section of the Tevatron enclosure is depicted in Fig. 7. The bending will occur in three 8 *m* dipoles per half-cell as opposed to four 6 *m* dipoles in the present Tevatron. The new magnets have been designed so as to not require any major additions to the present liquid helium refrigeration plant nor to the present power supply network.

In order to bring the two proton beams into collision, the straight sections in the interaction regions need to be lengthened. To do so requires additional bending at each end of the IR. This can be achieved by 6.6 Tesla dipoles, which are the most technically demanding aspect of this project. Research and development of these magnets has already begun at Fermilab. A similar straight section design involving these magnets has also been developed for the injection/RF region at F0.

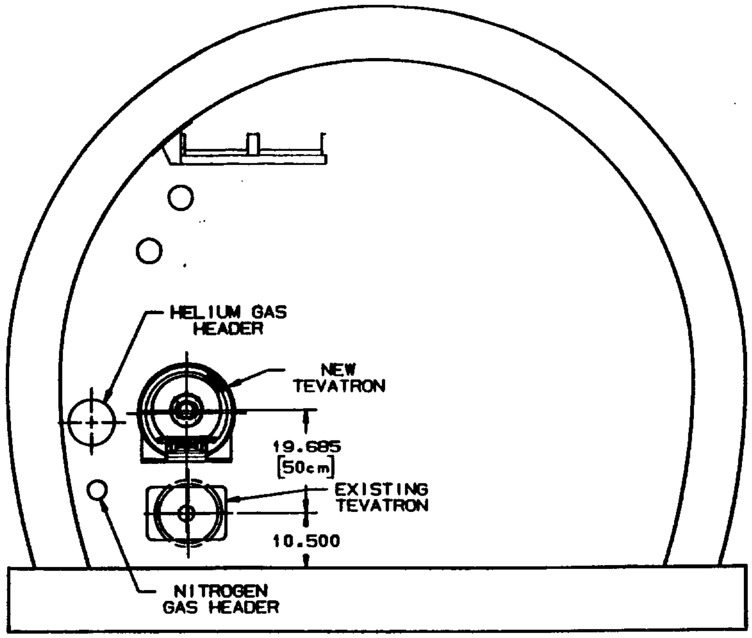

Fig. 7 — Tunnel cross section for the proton-proton collider project. The upper ring is the new superconducting accelerator, while the lower ring is the present Tevatron.

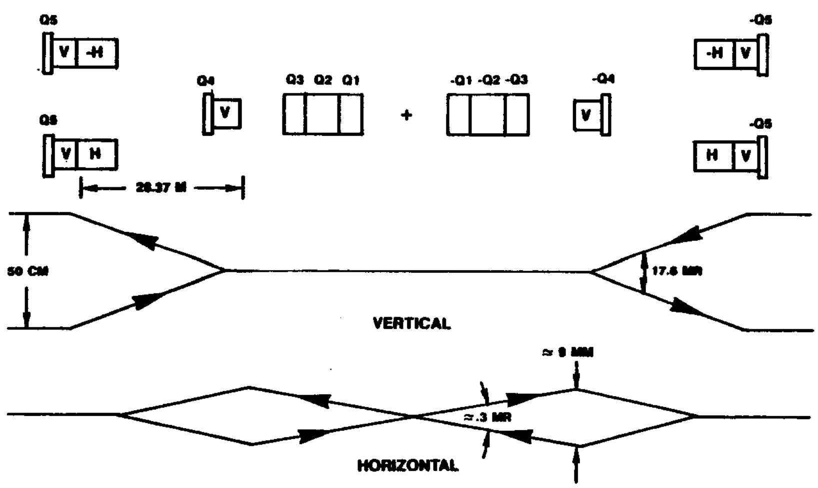

Fig. 8 — Interaction Region crossing geometry in the proton-proton collider project.

To ensure that bunches only collide at the interaction point, a small crossing angle must be introduced. Fig. 8 shows the crossing geometry through the IR. Below is a table of the pertinent collider parameters.

pp Collider Parameters

Number of Interaction Regions	2	
Free Space at IR	± 7.5	m
Transverse Emittance (Normalized)	6π	mm-mrad
β^*	0.25	m
Number of bunches	996	
Protons per bunch	1.4×10^{10}	
Crossing angle	1/3	mrad
Luminosity reduction due to above	$\sqrt{2}$	
Nominal Luminosity	2.0×10^{32}	$\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$
Interaction Rate at 100 mb	20	MHz
Interactions per bunch crossing	0.2	

4.3 Other Scenarios

The antiproton-proton upgrade option is the least expensive of the two explored so far. Its price tag is $\sim$ \$124 million, including R&D. The exacting and highly technical aspects of this scenario give it the least potential for growth. Though, on paper, it can make an initial luminosity of 50 times the Tevatron I design, this number is thought to be a true upper limit. On the other hand, the proton-proton option is very straight forward. The potential for growth to the very high luminosity era is quite evident. Of course, this scenario is much more costly, coming in at a price of $\sim$ \$285 million (R&D included).

With the need for higher field magnets for the proton-proton option comes the question of using these magnets to build a higher energy proton-antiproton collider. One could imagine accepting the lower luminosity as produced by the near-term upgrades discussed earlier in exchange for a 50 percent increase in center-of-mass energy. The fixed target program could also benefit greatly from the increased energy output of the new Tevatron. However, to extract high intensity beams at this energy, either toward the switchyard or toward a beam abort, may require even higher strength magnets in order to lengthen the long straight sections of the accelerator.

One of the more interesting new schemes might be a combination of the two options. Removal of the Main Ring from the main accelerator enclosure would be desirable for the antiproton-proton collider as well as for accelerator operations. Spray and background from the Main Ring during antiproton production are a nusance for the experimentalists, and the inherent interference between the Main Ring and Tevatron accelerators occupying the same tunnel has often caused operational difficulties as well. One could foresee moving the Main Ring to a new enclosure and building a ≥ 1.5 TeV proton-antiproton collider which will operate at an initial luminosity of $\sim 8 \times 10^{30} cm^{-2} sec^{-1}$. This scheme allows for the possible future expansion to proton-proton physics if desired.

It may even be possible to push the magnet field higher, toward the 2 TeV level. If a new machine were to be used at this higher energy only during collider operation with low intensity bunches, an internal abort system (such as the one presently used for 1 TeV antiprotons) may be sufficient, hence bypassing the question of longer straight sections. (This feature may also need to be incorporated into a 1.5 TeV design as well.) During fixed target operation, the accelerator could be used at a lower energy dictated by the extraction long straight section length.

Undoubtedly many other possible scenarios exist and will be contemplated in the upcoming months.

5 CONCLUDING REMARKS

Neither the pp option nor the $\bar{p}p$ option were submitted as proposals to DOE. It was felt that issues such as luminosity vs. energy upgrades, the desire for a third interaction region at Fermilab, upgrades to the present collider detectors, and the desire for fixed target test beams to be available during colliding beams operation, to name a few, needed to be addressed. An accelerator facility group at the Snowmass summer study discussed the technical issues associated with the above options. The group concluded that if 6.6 Tesla dipoles could be built, the 50 m straight sections of the present Tevatron lattice should be able to accomodate the extraction of 1.5 TeV beams to the fixed target program. [5] To go higher in energy would require the lengthening of the straight section using even higher field magnets. It was concluded that the highest practical energy limit for the Fermilab main enclosure was about 1.8 TeV. This would require 8 Tesla dipoles for the main bends and 8.8 Tesla dipoles

[5] M. Harrison, private communication.

at the ends of the lengthened straight sections. Development of realistic magnets of this strength is probably several years away.

It is clear that a major initiative is required to continue to meet the laboratory's goal of doubling the integrated luminosity each collider run from now until the beginning of SSC operation for physics in the late 1990's. Based on the results of the Snowmass workshop and other in-house discussions, a new Main Injector is being considered as a first construction project. Along with this, a 6.6 Tesla magnet design and prototype effort will proceed. Any upgrade option would benefit from these two projects. Next, a high field Tevatron design will be produced. This project, if funded, will see a new superconducting ring installed in the main enclosure in the space obtained by the removal of the Main Ring. This ring would be used for 1.5 TeV proton-antiproton colliding beams and for 1.5 TeV fixed target physics. It would then be possible to switch to proton-proton collisions at some future date, if the laboratory were to decide to pursue this route.

While many of the results from the previous two upgrade studies may be used, much work needs to be done for this new proposal. A new design report will be presented to DOE by early 1990 for funding in the 1991 fiscal year.

Acknowledgements

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